

Ocean Deoxygenation: Past, Present, and Future

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To a first order, the oxygen content of the ocean interior is determined by the influx of the gas across the air-sea surface (i.e., ventilation) and consumption due primarily to microbial respiration. As these two competing processes vary in space and time, so does the concentration of oxygen in the ocean interior. Although oxygen concentrations on continental margins are declining in many regions due to increased anthropogenic nutrient loadings [e.g., Rabalais *et al.*, 2002], oxygen also appears to be declining in both the central North Pacific Ocean and the tropical oceans worldwide [Emerson *et al.*, 2004; Whitney *et al.*, 2007; Keeling *et al.*, 2010] (see Figure 1). It is unclear whether the loss throughout the basins in the open ocean is a long-term, nonperiodic (secular) trend related to climate change, the result of natural cyclical processes, or a combination of both (Figure 2). If related to climate change, a number of important factors may be involved, including decreased solubility of oxygen as waters warm, decreased ventilation at high latitudes associated with increased ocean stratification, and changes in respiration in the ocean interior.

The potential consequences of ocean oxygen loss are profound. Long-term declines could lead to reduced biological productivity and diversity, altered animal behavior, declines in fisheries, redistributions of communities, and altered biogeochemical cycles. Environmental feedbacks may also result, potentially including increased production of greenhouse gases such as nitrous oxide and methane. In the geological past, major shifts in ecosystem structure and even mass extinctions occurred during periods when ocean oxygen content was low. Careful examination of past and current

oxygen concentrations highlights progress scientists have made in understanding oceanic responses to climate change and other externalities, but simultaneously reveals large gaps in information that prevent reliable predictions of conditions in the coming century [e.g., Deutsch *et al.*, 2006].

The Past

Oxygen plays a major role in the evolution of life and in coupling biogeochemical cycles. The rise of oxygen in Earth's atmosphere about 2.4 billion years ago was caused by, and contributed to, the evolution of life, including the first appearance and proliferation of animals roughly 600 million years ago [Knoll and Carroll, 1999]. Subsequent intervals of low atmospheric oxygen levels contributed to oceanic hypoxia and marine biotic crises throughout the Phanerozoic (542 million years ago to the present). Indeed, elemental, mineralogical, isotopic, molecular, and paleontological records preserved in Phanerozoic sedimentary rocks point to numerous oceanic anoxic events, some of which appear global in scale. During the Middle Devonian to Early Carboniferous

periods (385–360 million years ago), widespread anoxia in shallow continental seas coincided with an extended biotic crisis. Anoxia was also widespread in both shallow marine and deep ocean environments during the Permian-Triassic extinction (~252 million years ago), marked by the loss of approximately 90% of all marine animal taxa [Erwin, 2006].

The triggers for anoxia in the geological record are not well understood. Continental configuration and climate are clearly critical, insofar as these factors influence ocean circulation and hence the sites and extent of ventilation of the ocean interior [e.g., Zhang *et al.*, 2001]. Indeed, most of the ocean anoxic events occurred during times when both atmospheric carbon dioxide and inferred temperature were high. However, long-term events leading to mass extinctions are often associated with additional triggers, most commonly large-scale tectonic processes such as volcanism, the emplacement of large igneous provinces, or the potential outgassing of methane from shallow sedimentary deposits.

For more recent geological history, analyses of the marine oxygen suggest coherent patterns of contraction of oxygen minimum zones (OMZs) during cold periods and dramatic expansions of OMZs during warm intervals [Galbraith *et al.*, 2004]. Recent work suggests that the expansions of OMZs over the past roughly 2 million years were not synchronous between the Northern and Southern hemispheres but instead

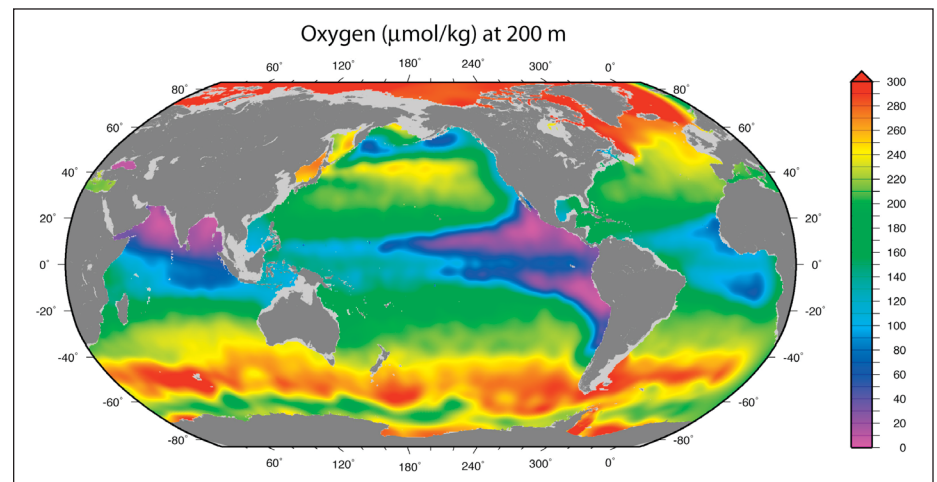


Fig. 1. Mean global ocean oxygen concentrations at 200 meters below the surface. Note the extensive regions of low oxygen (oxygen minimum zones) throughout the low-latitude oceans and the subarctic Pacific. Data from the World Ocean Circulation Experiment Global Hydrographic Climatology [Gouretski and Koltermann, 2004].

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progressed in lockstep with atmospheric warming in the respective hemispheres [Robinson *et al.*, 2007]. The overwhelming message emerging from the historical record is that the extent of oxygen-depleted waters is very sensitive to climate.

The Present

Accurate measurements of oceanic oxygen concentrations prior to about 1960 are scarce, and reliable, long-term observations from the open ocean are even scarcer. There are two relatively long records of observations in the open waters of the North Pacific with high-quality measurements spanning about 50 years [Whitney *et al.*, 2007] (Figure 2). These data indicate a roughly 20-year cycle of varying oxygen concentration superimposed on a monotonic (i.e., secular) decrease of about 0.7 micromole per kilogram per year. The cycle in oxygen concentration has been correlated with an 18.6-year periodic fluctuation of the diurnal tide of the ocean due to lunar precession [Whitney *et al.*, 2007; Keeling *et al.*, 2010]. This process is believed to affect ocean ventilation by increasing mixing near the Kuril Islands at the mouth of the Sea of Okhotsk [Yasuda *et al.*, 2006], a key area where intermediate waters form in the North Pacific (Figure 1). The monotonic decrease could be the limb of a longer cycle, or it may be a response to more restricted ventilation because of anthropogenically induced global warming.

Deoxygenation is often more dramatic on continental margins than in the open ocean. Continental margin upwelling systems are particularly prone to deoxygenation because their source waters are already low in dissolved oxygen and the high flux of nutrients in such areas (e.g., the Benguela upwelling region on the Atlantic side of southern Africa and the Peruvian upwelling region off the west coast of central Latin America) often leads to high phytoplankton biomass that sinks and is respired at depth. This process, which can be greatly exacerbated by anthropogenic eutrophication of semienclosed coastal waters, can lead to massive fish kills (e.g., the Mississippi plume described by Rabalais *et al.* [2002]).

The relative roles of on-shelf biogeochemical cycling versus source water secular trends are unclear. Off the U.S. West Coast, upwelled waters carry sufficient nutrient loads to induce extreme deoxygenation, at least when photosynthetic products are trapped and respired locally. Such conditions are observed only intermittently, however, suggesting that organic carbon is normally transported to the adjacent deep ocean in other years [Hales *et al.*, 2006]. The necessity of this deep-ocean export suggests a reason for the proximity of ocean interior OMZs and continental margin upwelling systems [e.g., Stramma *et al.*, 2010]. If a majority of the organic matter produced

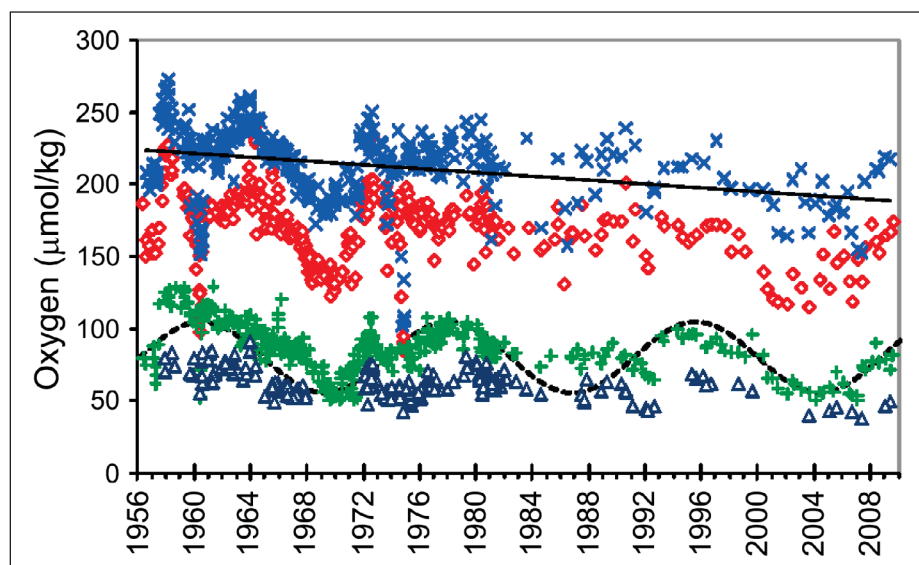


Fig. 2. The decadal trend and oscillations in oxygen concentrations on constant potential density surfaces (isopycnals). Data are shown for isopycnals 26.5 (blue crosses), 26.7 (red diamonds), 26.9 (green pluses), and 27.0 (dark blue triangles) at Ocean Station P (50°N, 145°W). Solid line is the linear regression of the 26.5 isopycnal showing an annual oxygen loss rate of 0.67 micromole per kilogram. The dashed sine wave shows that the oscillation on the 26.9 isopycnal has an amplitude of 50 micromoles per kilogram (centered on 80 micromoles per kilogram) and a period of 18.6 years [Whitney *et al.*, 2007; F. Whitney, personal communication, 2011].

in upwelling systems were exported to the adjacent ocean interior, then the respiratory consumption in these areas would increase, leading to further declines in oxygen concentrations in the ocean interior [Deutsch *et al.*, 2006].

The Future

Analysis of relatively long term databases in the contemporary ocean indicates trends of deoxygenation in upwelling areas along continental margins and shoaling of the depths of critical oxygen concentrations [Bograd *et al.*, 2008]. Even moderately long term trends in declining source water oxygen and increasing nutrient concentrations will cause currently intermittent but extreme deoxygenation conditions to become more frequent, intense, and persistent. Thus, although deoxygenation may be a scientific issue, its impact on global fisheries may be profound. For example, oxygen-depleted waters are associated with the migration of affected fish stocks from the California Current System (F. Whitney, personal communication, 2011).

The best tools for assessing future anthropogenic influence on ocean oxygen concentrations are global circulation models that succeed in reproducing observed changes over the past half century and include forcing due to future global warming. In nearly every case, predicted concentrations of oxygen decrease in the open ocean because of decreased ventilation due to stronger stratification [Oschlies *et al.*, 2008]. However, current

coupled three-dimensional general circulation models do not resolve nearshore waters well enough to predict future trends in these regions. Future measurements should focus on determining the validity of the predicted open ocean trends and the intensity of nearshore deoxygenation and its biological consequences and feedbacks.

Time series of reliable oxygen concentrations are surprisingly sparse in the contemporary ocean, and hence patterns are difficult to discern with certainty. To better understand the feedbacks between climatic changes and ocean oxygen concentration, resources are required to design and implement long-term ocean-observing networks, models, and analyses of historical data. To this end, the Ocean Observing Network, a multi-institutional project sponsored by the U. S. National Science Foundation, with its focus on in situ sensors mounted on both gliders and moorings (see the online supplement to this *Eos* feature at http://www.agu.org/journals/eo/v092/i046/2011EO460001/2011EO460001_suppl.pdf) and remotely sensed data of upper ocean phenomena including color, sea surface temperature, wind speed, and sea surface height, will provide an invaluable set of data for the coming decades. But this is still insufficient. Data must be obtained from remote regions and sustained over long periods (multiple decades). The needed time series of ocean oxygen and physical, chemical, and biological phenomena requires a commitment to such long-term observing campaigns, without which our ability to quantify the long-term health of the oceans is put at risk,

along with society's potential ability to sustainably obtain resources from ocean margins in the coming centuries.

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